Dealing with insufficient data: metadata modelling and stochastic exploration of the decision space

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Abstract: In Integrated Water Resources Management, a conjunctive consideration of hydrological processes and human influences is essential. Even though a large variety of hydrological models is available for this purpose; the application of these models is often hampered by insufficient data and information. In particular human impacts can not be described in detail. To cope with these problems a metadata modelling approach in form of a dynamic water balance was used, incorporating model-based analyses of the hydrological conditions and human impacts based on socio-economic statistics as well as on detailed studies of water utilisation in agriculture, industries and settlements. Interlinks of the human and the natural systems were categorised by water fluxes. These fluxes are modified within the planning process with the aim of attaining a sustainable groundwater balance. To reach this goal a large number of combined strategies can be applied and evaluated on basic criteria that define cost efficiency, e.g. groundwater recharge versus costs. Despite the sparseness of data, these two basic criteria can be specified by technological analyses. However, implementation of the strategies also depends on socio-economic uncertainties. It is suggested to summarise these criteria in an "acceptance estimate". This degree depends on known unknowns, e.g. of developments of the market, but also on human factors e.g. the unexpected outcome of participative processes. Within the planning process a stochastic generator for combinations of planning strategies is used. It derives combined strategies, which can be assessed in their hydrological effectiveness with the dynamic water balance model. The large numbers of possible strategies are ordered by their acceptance estimates, which are specified in a fuzzy based approach. This methodology was applied for ground-water management planning in a coastal region of China, which is strongly affected by saltwater intrusion.

Keywords: IRWM; acceptance estimate, water balance, crop change, China

1. INTRODUCTION

The scientific and technical literature boasts an abundance of measures, techniques and policies to alleviate deficits in water supply [Blanke et al. 2007; Fontane et al. 1995]. Their possible merits vary from a localised few hundred cubic metres reduction in irrigation water losses [Bjornlund 2010; Brouwer 2005] over city-wide thousands cubic metres of rainwater collection [Patel et al. 2008], to inter basin water transfers of millions of cubic metres of water [Cai 2008; Ghassemi et al. 2007]; from replacing water faucets in households [Governing Board of the

National Research Council 2005; National Development and Reform Commission 2005] over province-wide crop changes [Bishop et al. 2010] to high-tech nuclear desalination plants [El-Dessouky et al. 2002; Wang et al. 2003]. Since it is unfeasible to calculate the impacts of all potential measures using detailed hydrological models, the question of arises of how to objectively select the measures, suitable for the local parameters and problems, to be studied in detail. Most studies seldom deal with this problem and those that do often indiscriminately compare the different water quantities saved across different sectors, neglecting their often very contrasting effects on the water balance [Addams et al. 2009].

To objectively select promising measures without time-consuming and data-intensive models, a metadata modelling approach in form of a dynamic water balance tool was developed. The dynamic water balance tool incorporates model-based analyses of the hydrological conditions and human impacts based on socio-economic statistics as well as on detailed studies of water utilisation in agriculture, industries and settlements. This tool facilitates the comparison of water saving techniques across sectors according to their actual impact on the water balance and its deficits, taking into account the local hydrological processes and human influences.

This last factor: human influences, impacts and changes thereof, are often very hard to quantify and model because of insufficient data and information [Alcamo et al. 2007; Vörösmarty et al. 2000]. It is nevertheless an essential component in integrated water resources management and often even one of the main causes of drought [Jing et al. 2012]. The next obstacle in the objective selection of promising measures is the problem of appraising anthropological, cultural, historical social and economical constraints. Based on the principle that the current status is the resultant of these societal unknowns, one can state that a measure-induced divergence of this status infringes one or more of these parameters. Thus the problem of insufficient data is circumvented and the best measure is one that optimises its targets (like water saving) and at the same time minimises a divergence of the current status. The second tool presented here does just that.

2. METHODS & TOOLS

2.1 The metadata modelling approach

In dealing with an overwhelming amount of possible measures with which to alleviate drought, one of the first steps is to find a common denominator by which each measure can objectively be compared. It is clear that a m³ of harvested rainwater differs from a m³ imported from another basin. In the first case, this water amount is reallocated from a possible surface or soil water compartment to municipal or industrial use; in the second case this amount of water is added to the total balance. Generally, drought-reducing measures change natural and/or anthropogenic water fluxes and their effects upon a certain deficit cannot be compared across compartments and without taking the existing local fluxes and compartments into account.

We built a metadata model, describing Falkenmark & Rockström's [2006] blue and green water flows (cf. figure 1) and added anthropogenic compartments and fluxes.
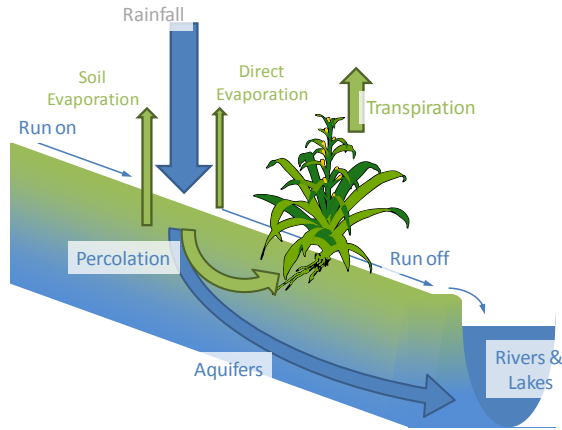
Figure 1. Agrohydrological flows indicating green and blue water flows. (After Rockström [1999])

The tool was programmed in Excel© and the quantities of all individual compartments and fluxes can be changed in the spreadsheet based on local conditions and more detailed hydrologic models. A user interface (GUI) allows easy interaction with decision makers. All relevant parameters can be changed using sliders or input boxes, calculating and visualising on the fly major fluxes, compartments and deficits. The GUI toolbox also offers the decision maker a choice of measures to integrate into the water balance and see their impact dynamically across the compartments. More importantly, the metadata model translates the effects of individual and combined measures on each compartment, thus allowing an objective comparison of all possible measures.

2.2 The acceptance estimate approach

Implementation of the selected strategies also depends on socio-economic uncertainties. We suggest to summarise these criteria in an "acceptance estimate" which depends on known unknowns, e.g. of developments of the market, but also on human factors e.g. the unexpected outcome of participative processes. For instance, the actual agricultural land use pattern can be seen as the end result of a multitude of physical, social and economical constraints. Any deviation from this pattern will decrease the acceptance estimate. This means no crop change will have an acceptance estimate of one. Based on historical market fluctuations, crop and local economy specific boundaries can be set that, when crossed, cause a reduction of this acceptance estimate to approach zero. For the interpolation between both extremes, different distribution functions can be used, symmetrical or asymmetrical. The proposed methodology is independent of the distribution selection. For most criteria, there are no real arguments against a normal distribution, which will be used exemplary. In order to compare between different dimensions and scales, the deviation has to be normed like for instance in (Eqn. 1).

$$D_{Ac} = \frac{A_c' - A_c}{A_c} \quad (1)$$

With D_{Ac} the deviation from the current state of parameter A for alternative c, A_c' the changed amount of parameter A for alternative c and A_c the current amount. A site and sector specific estimate for a plausible and acceptable deviation from the actual area distribution can be calculated based on the standard deviation of historical fluctuations using (Eqn. 2):

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^2} \quad , \text{where} \quad \mu = \frac{1}{N} \sum_{i=1}^{N} x_i \quad (2)$$

With *N* the number of alternatives and x_i the historical values of *A,* the acceptance estimate for alternative c then becomes:

$$l_c = f(D_c) = e^{-\frac{D_c^2}{2\sigma^2}} \quad (3)$$

Which means that the summarised acceptance (*D*) of all measure induced changes is then:

$$DA = \prod_{c=1}^{n} l_c \quad (4)$$

This variable also drastically reduces the decision space and therefore also the computational effort. In most cases, reducing the water usage will limit or at least affect a parameter of productivity leading to a more or less pronounced dependency (cf. figure 2).
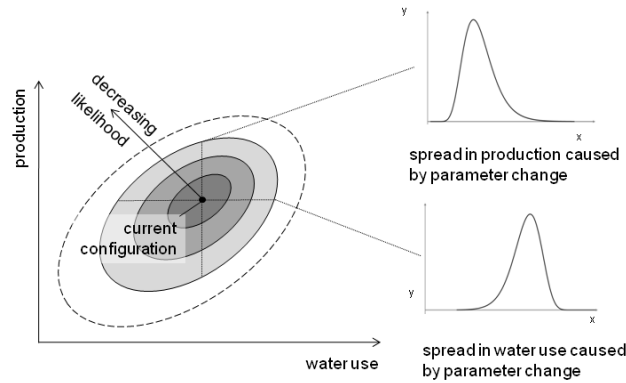

Figure 2. Schematic representation of stochastic distribution around the current state

It is clear that the stochastic distribution around the current state can be divided in four quadrants (cf. figure 3). This means that, besides the acceptance, based on the diversion from the current situation *DA*, a direction oriented part has to be added to the degree of acceptance *DA*.
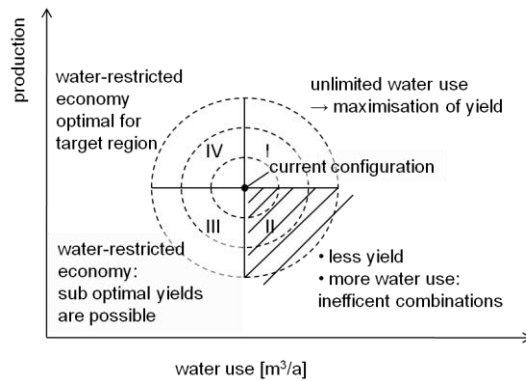

Figure 3. Definition of four quadrants around the original distribution

In calculating and norming the distance to the pareto font, based on the distance of the original distribution to the pareto front, the distance to pareto *d* can be normalised and a combined acceptance *CA* calculated by multiplying the normalised distance with the acceptance degree based on divergence (5).

$$CA = DA \left(1 - \frac{d}{d_{max}} \right) \quad (5)$$

2.3   The spatial aspects

Solving IWRM-issues does not end with determining measures and quantities/acceptance. The geographical location of where to apply these measures is not only directly dependent of the previous analyses, but it also influences both measures and quantities/acceptance. The metadata water balancing approach delivers a first, rough, localisation of measures into different sectors like irrigation in agriculture, water harvesting in cities etc. The second step, the quantification/acceptance approach refines this localisation like for instance drip irrigation only in orchards or water harvesting only on large industrial complexes.

Optimally, both measures selection and quantification should be re-evaluated on a sub-basin level and compared to the overall goal. If, after selection and dimensioning of measures in each sub basin the overall goal is not achieved, solutions where the acceptance estimate is lower have to be selected along the pareto-optimal line in quadrant IV (cf. figure 3). Since water use efficiency is a main factor, sub basins where the slope of the pareto line is lowest should be targeted first. Depending on the standard deviation used in the acceptance estimate (Eqn. 2) and the water use/production dependency (cf. figure 2), it is even possible to follow the pareto line slightly into section III without drastically reducing the acceptance. If the overall goal is still not achieved, inter-basin measures should be evaluated, starting in the upstream directions.

3.   APPLICATION

3.1   Study area

The Shandong Province, especially the Huangshui river basin, is an outstanding example for water conflicts arising from fast growing population, industry and agriculture. Social status and income of farmers in the Shandong province is significantly below a level that would allow them to keep up with the technology development in irrigation and farming. The Huangshui basin measures about 1560 km², with an input of 551 mm rainwater per year. The water demand exceeds the water resources by 7%, causing the rivers to dry out most of the year, groundwater tables to decrease and salt water to intrude along the coast.

3.2   The metadata modelling approach

To calibrate the metamodel's coefficients governing the individual fluxes, a detailed 1-D empirical groundwater model SIWA was used [Monninkhoff et al. 2011]. This takes into account land use, soil type, inclination, and ground water level to calculate run off and percolation coefficients. Anthropogenic influences and needs were calibrated using the model WBalMo [Kaltofen et al. 2008] which allowed a detailed quantification of these influences and needs that form an intrinsic part of the water balance. Its water fluxes can be depicted as natural flows (arrows in Figure 4) between blue and green compartments and anthropogenic influences (dotted arrows) between natural and anthropogenic compartments (red).

A catalogue of all measures to alleviate deficits in water supply can be accessed through the GUI. Each measure, when implemented, modifies the fluxes within the water balance allowing all measures to be compared based on their efficiency in attaining a sustainable water balance. This way, a large number of combined strategies can be applied and evaluated on basic criteria that define cost efficiency, e.g. groundwater recharge versus costs. Despite sparseness of data, these two basic criteria, specified by technological analyses, can provide a clear preferential selection of the measures based on local conditions.
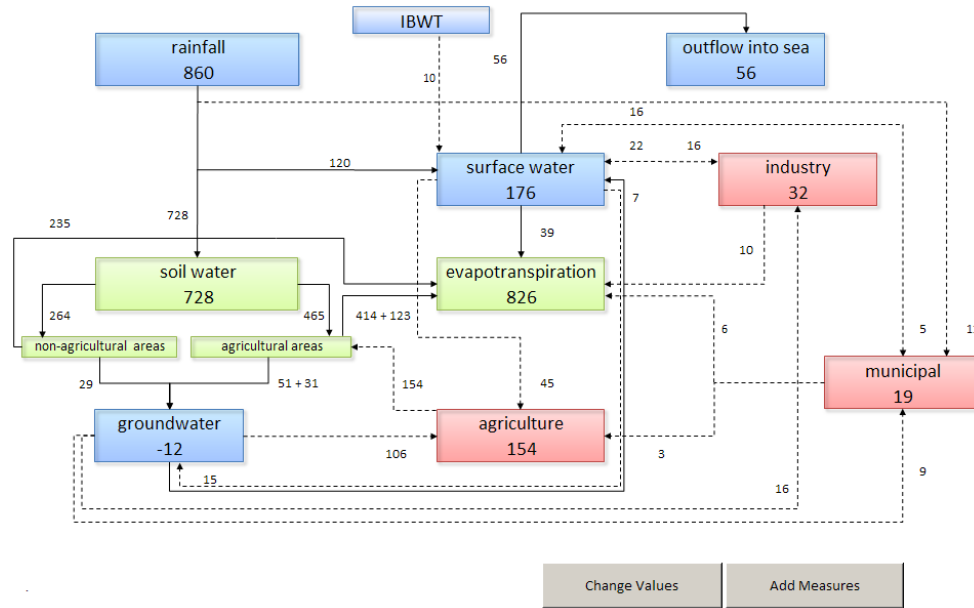
Figure 4. Dynamic Water Balance. Exemplary two measures are activated: rainwater harvesting and inter basin water transfer (all numbers in Mio m³/year).

In the study area, crop changes seemed to be one of the most cost-effective measures based on the meta-data modelling approach. To quantify the amount of water to be saved by this measure without extensive sociologic, agrologic and economic studies, the second tool was developed.

3.3   The acceptance estimate approach

If the current crop distribution is defined as the result of a multitude of physical, social and economic constraints, then the degree of deviation from this pattern can be expressed by the reduction of the degree of acceptance (Eqn. 3). A deterministic-stochastic model generates area defined crop changes (A_c). The total area was set to remain constant for crop changes since increase or decrease in agricultural area was treated as another independent measure in the measure catalogue. For each change, the acceptance estimate was calculated using (Eqn. 4). Additionally, for each shift, the crop-specific and irrigation type-specific water usage (w_{ci}) and potential yield (y_{ci}) was determined. Thus, the deterministic-stochastic model produces a cloud of likely crop change measures, each with three parameters: the acceptance (DA), total water use (W) and yield (Y) according to (Eqn. 6 and 7).

$$W = \sum_{c=1}^{n_c} \sum_{i=1}^{n_i} A_c w_{ci} p_{ci} \quad (6) \quad \text{and} \quad Y = \sum_{c=1}^{n_c} \sum_{i=1}^{n_i} A_c y_{ci} p_{ci} \quad (7)$$

p_{ci} being the irrigation type distribution (percentage) for each crop type.

Adding the distance to the pareto front in quadrant IV (see figure 3), the total acceptance estimate was calculated using (Eqn. 5) (see figure 5).

This allowed us to select the most likely crop changes to be realised and quantify water savings, despite unknown socio-economic parameters.
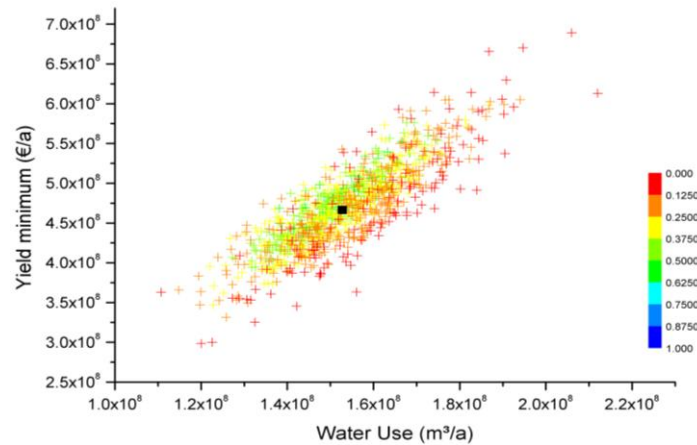
Figure 5. Stochastic simulation of crop changes categorised by their acceptance estimates. The black square represents current crop use.

These agricultural changes can objectively be compared against, for instance, industrial water saving techniques based on their respective effects on groundwater recharge using the metadata modelling approach described above.

3.4 The spatial aspects

Since it is usually impossible for a larger study area to calculate hundreds of groundwater scenarios, we adopted a two track system. Groundwater simulations were run to calculate and situate the required amount of water to stop the saltwater intrusion, independent of measures and their combinations. Afterwards, the measures were spatially located and dimensioned according to the procedure in §2.3.

4. EVALUATION & CONCLUSIONS

We have developed a deterministic-stochastic methodology that allows the incorporation of unknown parameters in the quantification of water management strategies, partially overcoming an all too common lack of data. To achieve this, we introduced a parameter called the acceptance estimate. This allowed for a quantification of less-technical and societal influenced aspects in an extensive water management measure catalogue, spanning a multitude of economical sectors all influencing the basin's water budget in geographically different areas, in different compartments of the water cycle.

We have also developed a methodology that allows for an objective comparison of water management measures across the sectors and compartments using a dynamic water balance model that transforms differentiated effects to a common denominator. Using both methods of the meta-data approach, we were able to formulate location specific measures with a high acceptance estimate and a high positive impact of the sustainability of the local hydro-ecosystem.

This methodology was applied for groundwater management planning in a coastal region of China, strongly affected by saltwater intrusion. The results were used as input for a detailed FEFlow[®]-MIKE11[®] model, which proved that the generated measures, besides having a minimal impact on the agro-economical system, were able to halt the saltwater intrusion within the 40 year simulation period.

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